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A review on energy and exergy analysis of solar dying systems

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ABSTRACT

Solar energy is a clean, abundant and freely available renewable energy sources. Energy and exergy analysis of solar thermal devices has drawn considerable interest among the researchers across the world. Solar drying is the promising option to utilize low grade energy to dry agricultural produces. Exergy analysis is a tool to access the efficient usage of solar energy. It is the property of the system, which gives the maximum power that can be distracted from the system when it is brought to a thermodynamic equilibrium state from a reference state. Using exergy analysis, based on the first and second laws of thermodynamics, it is possible to infer the true potential of different kinds of energies. In this paper, a holistic approach on energy and exergy analysis of solar dryer with case studies has been made.

Contents

1. Introduction

Drying of agricultural produces is a very simple, ancient skill. Right from the ancient age drying with solar is one of the most accessible and widespread drying technology. Developing and under nations are still adapting drying technology largely unchanged from ancient times. Solar drying seems promising options for agricultural produces preservation in tropical and subtropical areas because these areas receive abundant sunshine hours and appreciable solar intensity. There is no doubt that open solar drying offering low capital and operating costs and little expertise is required. On the other hand contamination, theft or damage by birds, rats or insects; slow or intermittent drying and no protection from rain; low and variable quality of products due to over- or under-drying; large areas of land needed for the shallow layers of food are the major disadvantage of open sun drying.

Drying is nothing but it defined as removal of moisture from the products and is a most important process for preserving agricultural products since it has a great effect on the quality of the dried products. Drying of fruit and vegetables is one of the oldest methods of food preservation. The major objective in drying agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended period [1].

In the present context, current trends towards higher cost of fossil fuels and uncertainty regarding future cost and availability, applications of solar dryer in drying agricultural produces will probably increase and become more economically feasible in the near future. Solar dryer give faster drying rates by heating the air to 10–30 °C above ambient, which causes the air to move faster through the dryer, reduces its humidity and deters insects. Drying is a complex process involving heat and mass transfer between the product surface and its surrounding medium and within the product [2].

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Nomenclature

Symbols

$\dot{m}$	mass flow rate, kg/s
w	specific humidity, g g^{-1}
$\dot{W}$	energy utilization, J s^{-1}
$\dot{Q}$	net heat, kJ/s
V	velocity, m/s
h	enthalpy, kJ kg^{-1}
P	pressure, kPa
T	temperature, K
I	solar insolation, W m^{-2}
A_c	collector area, m^2
EUR	energy utilization ratio, %
u	specific internal energy, kJ kg^{-1}
s	specific entropy, kJ kg^{-1} K^{-1}
v	specific volume, m^3 kg^{-1}
z	altitude coordinate, m
J	joule constant
E	emissive power
F	shape factor
c_p	specific heat, kJ kg^{-1} K^{-1}
$\bar{c}_p$	mean specific heat, kJ kg^{-1} K^{-1}
g	gravitational constant, m s^{-2}
g_c	constant in Newton's law
Ex	exergy, kJ kg^{-1}

Subscript

a	air
i	inlet, inflow
o	outlet
mp	moisture of product
sat	saturated
da	drying air
dc	drying cabinet
∞	surrounding or ambient
ins	instantaneous
c	collector, chemical
$shno$	shelf number
L	loss

Greek symbols

ϕ	relative humidity, %
η	efficiency
μ	chemical potential, kJ kg^{-1}
η_{Ex}	exergetic efficiency, %

Thermodynamic analysis, particularly exergy analysis, has appears to be an essential tool for system design, analysis and optimization of thermal system [3]. Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment [4,5]. Exergy analyses can be applied on both system and component levels. It leads to a better understanding of the influence of thermodynamic phenomena on effective process, comparison of the importance of different thermodynamic factors, and the determination of the most effective ways of improving the process [6].

2. Energy and exergy analysis

There are number of experimental and theoretical studies on the solar drying process are available in literature [7–10]. The energy and exergy analysis is as follows.

2.1. Energy analysis

It is assumed that solar drying process is considered as steady flow process. During the solar dryer, first solar energy utilized to generate hot air in collector, hot air being cooled during drying process and became humidified. This air conditioning process considered as steady flow process that are analyzed by steady-flow conservation of mass.

General equation of mass conservation

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \tag{1}$$

General equation of mass conservation of moisture: $\sum(\dot{m}_{wi} + \dot{m}_{mp}) = \sum \dot{m}_{wo}$ or

$$\sum(\dot{m}_{ai}w_i + \dot{m}_{mp}) = \sum \dot{m}_{ai}w_o \tag{2}$$

General equation of energy conservation:

$$\dot{Q} - \dot{W} = \sum \dot{m}_o \left(h_o + \frac{V_o^2}{2}\right) - \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2}\right) \tag{3}$$

The changes in kinetic energy of the air flow were taking into consideration, while the potential and kinetic energy in other parts of the process were neglected.

During the energy and exergy analyses of drying process, the following equation were generally used to compute the relative humidity and enthalpy of drying air:

Relative humidity

$$\phi = \frac{wP}{(0.662 + w)P_{sat@T}} \tag{4}$$

where w denotes the specific humidity, P the atmospheric pressure, and $P_{sat@T}$ is the saturated vapor pressure of drying air.

The enthalpy of the drying air can be determined as follows:

$$h = C_{p_{daT}}T + wh_{sat@T} \tag{5}$$

where $C_{p_{da}}$ defines the specific heat of drying air, T the drying air temperature and $h_{sat@T}$ is the enthalpy of the saturated vapor.

2.2. Determination of the outlet conditions of the solar air heater

It is considered that the conditions of entry are those of the ambient conditions.

Useful energy received by the collector

$$Q_{da} = \dot{m}_{da}C_{p_{da}}(T_{da} - T_{\infty}) \tag{6}$$

The instantaneous efficiency of the solar air heater

$$\eta_{ins} = \frac{Q_{da}}{IA_c} \tag{7}$$

Determination of inlet and outlet condition of the drying cabinet

$$T_{da} = T_{dci}$$

$$\phi_{da} = \phi_{dci}$$

$$h_{da} = h_{dci}$$

$$w_{da} = w_{dci}$$

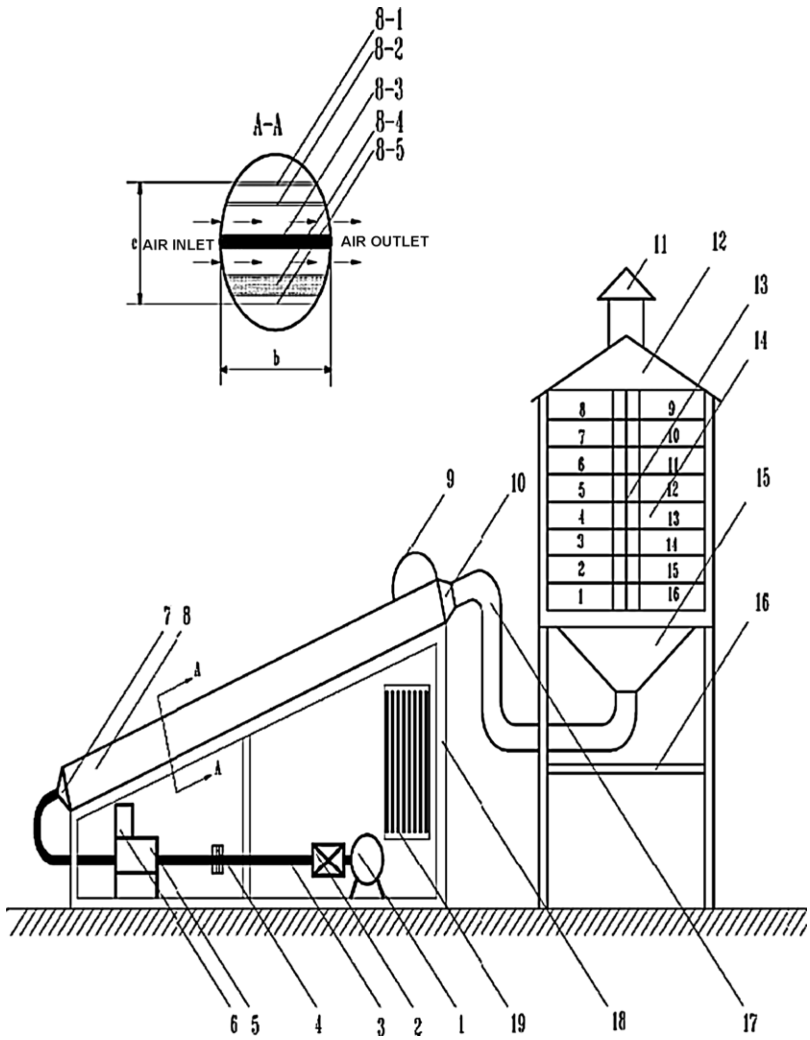

Fig. 1. Solar assisted drying cupboard (1. Fan, 2. Valve, 3. Connection pipe, 4. Orifice, 5. Auxiliary heater, 6. Temperature controller, 7. Inlet of solar air collectors, 8. Solar air collectors (2), 8-1. Glass cover, 8-2. Glass cover, 8-3. Absorber plate, 8-4. Insulation, 8-5. Wood cover, 9. Pyranometer, 10. Outlet of solar air collectors, 11. Chimney, 12. Outlet of drying cupboard, 13. Inter section, 14. Shelves, 15. Inlet of drying cupboard, 16. Support of drying cupboard, 17. Flexible connection pipe, 18. Support of solar air collector, 19. Manometer).

Energy used

$$Q_{dc} = \dot{m}_{da}(h_{dci} - h_{dc0}) \tag{8}$$

Energy utilization ratio of the drying chamber EUR_{dc} can be determined by mean of the following equation using the psychometric chart;

$$EUR_{dc} = \frac{\dot{m}_{da}(h_{dci} - h_{dco})}{\dot{m}_{da}C_{p_{da}}(T_{da} - T_{\infty})} \tag{9}$$

2.3. Second law analysis: exergy analysis

From the thermodynamics point of view, exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [4,11–14].

Exergy is a true measurement of the quality or grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering a thermal system is destroyed within the system due to irreversibilities. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems [15]. Exergy balance equation is written as suggested by [16].

$$\begin{aligned} Exergy = \underset{\text{internal energy}}{(u-u_{\infty})} - \underset{\text{entropy}}{T_{\infty}(s-s_{\infty})} + \underset{\text{work}}{\frac{P_{\infty}}{J}(v-v_{\infty})} \\ + \underset{\text{momentum}}{\frac{V^2}{2gJ}} + (z-z_{\infty})\frac{g}{g_cJ} + \underset{\text{gravity}}{\textstyle\sum_c(\mu_c-\mu_{\infty})N_c} \\ + \underset{\text{radiation emission}}{E_iA_iF_i(3T^4 - T_{\infty}^4 - 4T_{\infty}T^3)} + \cdots \end{aligned} \tag{10}$$

where the subscript ∞ denotes the reference conditions.

During the exergy analyses of different systems, there are few terms shown in Eq. (10) are used but not all. Since exergy is energy available from any source, it can be developed using electrical current flow, magnetic fields, and diffusion flow of materials. One common simplification is to substitute enthalpy for the internal energy and PV terms that are applicable for steady-flow systems. Eq. (11) is often used under conditions where the gravitational and momentum terms are neglected. In addition to these, the pressure

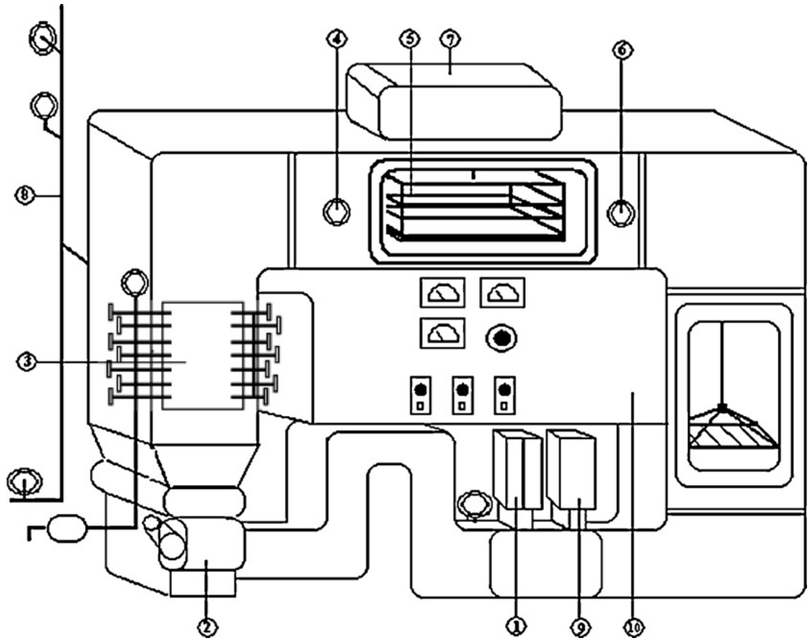

Fig. 2. Experimental set-up. (1) Adjustable flab, (2) fan, (3) heat exchanger, (4) wet and dry thermometers, (5) dry chamber, (6) wet and dry thermometers, (7) digital balance, (8) saturated steam line, (9) adjustable flab and (10) control panel.

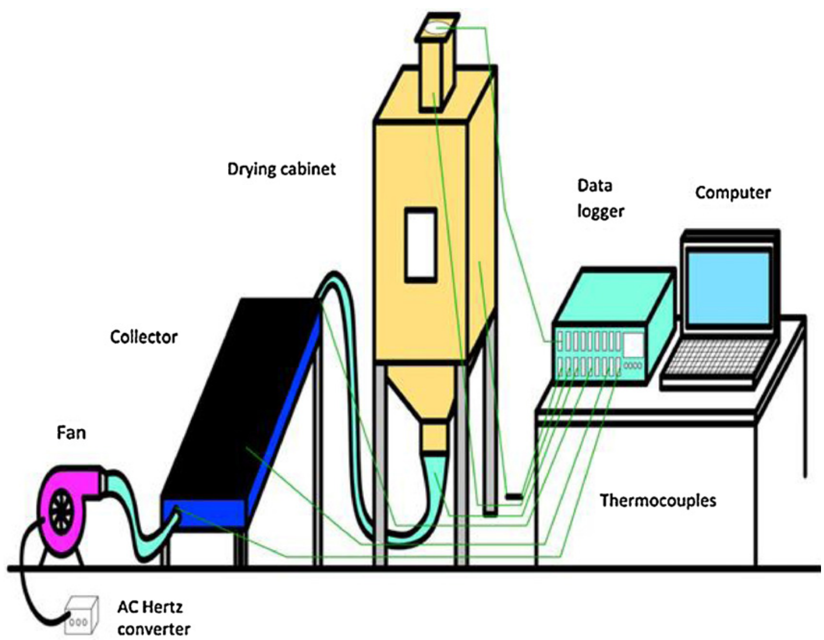

Fig. 3. Schematic view of the solar dryer system.

changes in the system are also neglected because of $v \approx v_\infty$, hence Eq. (11) is reduced as suggested by Prommas et al. [15] and Midilli and Kucuk [12];

$$Exergy = \bar{c}_p \left[(T - T_\infty) - T_\infty \ln \frac{T}{T_\infty} \right] \tag{11}$$

The equation of exergy inflow can be written for the shelves and the cabinet as

$$Ex_{shni} = Ex_{dci} = \bar{c}_{p_{da}} \left[(T_{shni} - T_\infty) - T_\infty \ln \frac{T_{shni}}{T_\infty} \right] \tag{12}$$

where $\bar{c}_{p_{da}}$ is average specific heat of drying air.

The equation of exergy outflow can also be written as follows

$$Ex_{shno} = \bar{c}_{p_{da}} \left[(T_{shno} - T_\infty) - T_\infty \ln \frac{T_{shno}}{T_\infty} \right] \tag{13}$$

Exergy outlet for solar drying cabinet

$$Ex_{dco} = \bar{c}_{p_{da}} \left[(T_{dco} - T_\infty) - T_\infty \ln \frac{T_{dco}}{T_\infty} \right] \tag{14}$$

$$Exergy = Exergy\,inflow - Energy\,outflow$$

$$\sum Ex_L = \sum Ex_i = \sum Ex_o$$

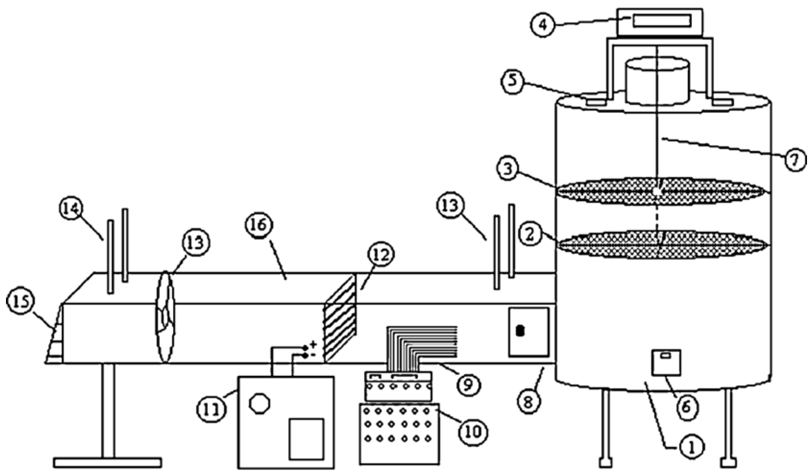

Fig. 4. Experimental setup. 1. Drying chamber, 2. 1st tray, 3. 2nd tray, 4. Digital balance, 5. Observation windows, 6. Digital thermometer, 7. The balance bar, 8. Control panel, 9. Thermocouples, 10. Digital thermometer and channel selector, 11. Rheostat, 12. Resistance, 13. Fan, 14. Wet and dry thermometers, 15. Adjustable flap, 16. Duct.

$$Exergetic\ Efficiency = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow}$$

$$\eta_{Ex} = 1 - \frac{Ex_L}{Ex_i} \tag{15}$$

2.4. Case studies

Luminosu and Fara [17] discussed operational conditions of flat plate solar collector by means of exergy analysis using numerical simulation technique. However, they assumed the exergy flow rate in the global solar radiation to be equal to the solar flux; the overall thermal loss coefficient, the heat removal factor, the efficiency factor, agent fluid properties and other heat transfer coefficients of the solar collector are constant. Also, they considered the fluid inlet temperature to be equal to the ambient temperature and constant. They neglected the destroyed exergy caused by the ducts' pressure drop.

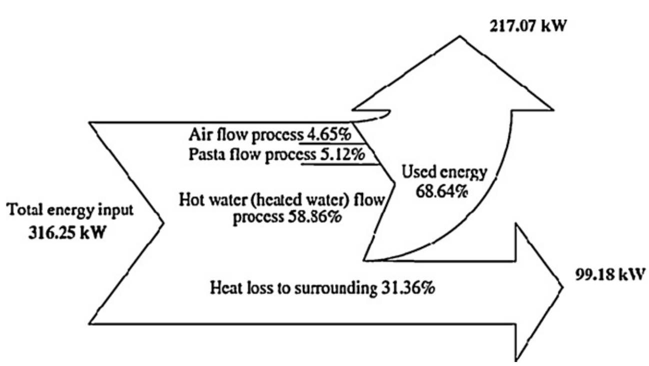

Fig. 5. Energy flow diagram of the whole system (given as the percentages of whole energy input).

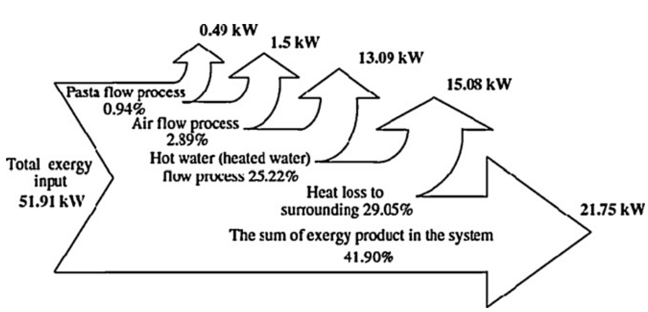

Fig. 6. Exergy flow diagram of the whole system (given as the percentages of whole exergy input).

Celma and Cuadros [18] conduct an experiment to access the energy and exergy analysis of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer. The essential drying parameters were monitored as per drying standard. Energy analysis was carried out by applying first law of thermodynamics; it is the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Exergy analysis was carried out by applying second law of thermodynamics. During the experimental study, it was found that exergy losses took place mainly during the second day, when the available energy was less used. The exergy losses varied in the range of 0 kJ kg^{-1} to 0.125 kJ kg^{-1} for the first day and between 0 kJ kg^{-1} and 0.168 kJ kg^{-1} for the second. The exergetic efficiencies of the drying chamber decreased as inlet temperature were increased, provided that exergy losses became more significant. In particular, they ranged from 53.24% to 100% during the first day, and from 34.40% to 100% during the second.

Midilli and Kucuk [12] accomplished energy and exergy analyses of the solar drying process of the shelled and unshelled pistachios under Turkey climatic conditions. The selected dryer having 16 number of shelves and in the experiments, the 2nd and 15th shelves were selected for the efficient utilization of drying air as shown in Fig. 1. However, the 1st and 16th shelves were kept empty so that hot air could be homogeneously diffused throughout the shelves inside of the solar drying cabinet. During the experiments it was found that shelled and unshelled pistachio samples were sufficiently dried in the ranges between 40 and 60 °C in 6 h. The unshelled pistachio samples consumed more energy than the shelled pistachio samples. The ratio of the energy utilization of the 15th shelf was higher than that of the 2nd shelf. It was reported that the most efficient use of exergy was achieved where and when exergy losses were minimum. The maximum value of the exergy inflow to the system was obtained as 3.718 kJ kg^{-1}. However, the exergy losses went up with the increase of the energy utilization in both the shelves and the solar drying cabinet. Although the most exergy losses took place during the solar drying of unshelled pistachios, the highest exergetic efficiency was obtained during the solar drying of shelled pistachios. The exergy losses were equal to zero at the point where the exergetic efficiency was estimated as 100% because drying process discontinued in the system. Consequently,

Fig. 7. Photovoltaic/thermal (PV/T) collector integrated with a solar greenhouse.

it is suggested that the order, structure, and moisture content of the products should be taken into consideration in order to decrease the energy utilization and the exergy losses.

Energy and exergy analyses of the thin layer drying of coroba slices at three different air temperatures (71, 82 and 93 °C) and velocities (0.82–1.00 and 1.18 m/s) were conducted by Corzo et al. [19]. The air dryer used for experimental study was fully equipped as illustrated in Fig. 2. They access the effects of inlet air temperature and velocity and drying time on both energy and exergy. It was found that both energy utilization and energy utilization ratio increased with increasing drying time while exergy efficiency decreased. The values of energy utilization and energy utilization ratio were found in the range of 0.009–0.65 kJ/s and 0.00007–0.008 from 71 °C to 93 °C with drying air velocities of 0.82–1.18 m/s, respectively. The values of exergy inflow and exergy outflow were found to be in the range of 0.33–0.87 kJ/s and 0.25–0.75 kJ/s from 71 °C to 93 °C with drying air velocities of 0.82–1.18 m/s, respectively. The values of exergy loss and exergy efficiency were found to be in the range of 0.005–0.010 kJ/s and 0.97–0.80 from 71 °C to 93 °C with drying air velocities of 0.82–1.18 m/s, respectively.

Akbulut and Durmus [20] conduct an experiment on the thin layer drying process of mulberry via forced solar dryer as shown in Fig. 3. Energy and exergy analysis of the drying process was accessed by employing first and second law of thermodynamics respectively. The energy utilization ratio were found as 55.2%, 32.19%, 29.2%, 21.5% and 20.5% for the five different drying mass flow rate ranged between 0.014 kg/s and 0.036 kg/s. The exergy loss were found to as 10.82 W, 6.41 W, 4.92 W, 4.06 W and 2.65 W with the drying mass flow rate varied between 0.014 kg/s and 0.036 kg/s. It was concluded that both energy utilization ratio and exergy loss decreased with increasing drying mass flow rate while the exergetic efficiency increased.

Akpinar et al. [21] analyzed the energy and exergy of the single layer drying process of potato slices via a cyclone type dryer as experimental setup shown in Fig. 4. On the basis of experimental results it was concluded that the exergy losses took place mostly in the 1st tray where the available energy was less utilized during the single layer drying process of potato slices. The potato slices are sufficiently dried in the ranges between 60 and 80 °C and 20–10% relative humidity at 1 and 1.5 m/s of drying air velocity during 10–12 h despite the exergy losses of 0–1.796 kJ/s.

Exergy analysis of drying process of a passively heated solar greenhouse has been investigated by Ozgener and Ozgener [22]. The experimental results indicate that these drying applications can be used for energy saving electricity, the number of barrels of oil, and cubic meters of natural gas in the Aegean region of Turkey. The average exergy efficiency of drying process is obtained as 63–73%. It was concluded that if solar energy gain is low, it can be said that passive solar-heated greenhouses can be used for pre-drying of products.

Ozgener and Ozgener [23] present an energy and exergy modeling of industrial final macaroni (pasta) drying. The total energy rate input to system was 316.25 kW. The evaporation rate was 72 kg h^{-1} (0.02 kg/s) and energy consumption rate was reported as 4.38 kW for 1 kg water evaporation from product. Humidity product rate was 792 kg h^{-1} (0.22 kg/s) and energy consumption rate was found about 0.4 kW for 1 kg short cut pasta product. The energy efficiencies of the pasta drying process and the overall system were found as 7.55–77.09% and 68.63%. The exergy efficiency of pasta drying process is obtained to be as 72.98–82.15%. For the actual system that is presented the system exergy efficiency vary between 41.90 and 70.94%. The heat losses to the surroundings and exergy destructions in the overall system are quantified and illustrated using energy (Fig. 5) and exergy (Fig. 6) flow diagrams.

Nayak and Tiwari [24] studied energy and exergy analysis of photovoltaic/thermal (PV/T) collector integrated with a solar greenhouse as shown in Fig. 7. The analysis was based on quasi-steady state condition. It was reported that the theoretical value

Fig. 8. Indirect type solar dryer for mint drying.

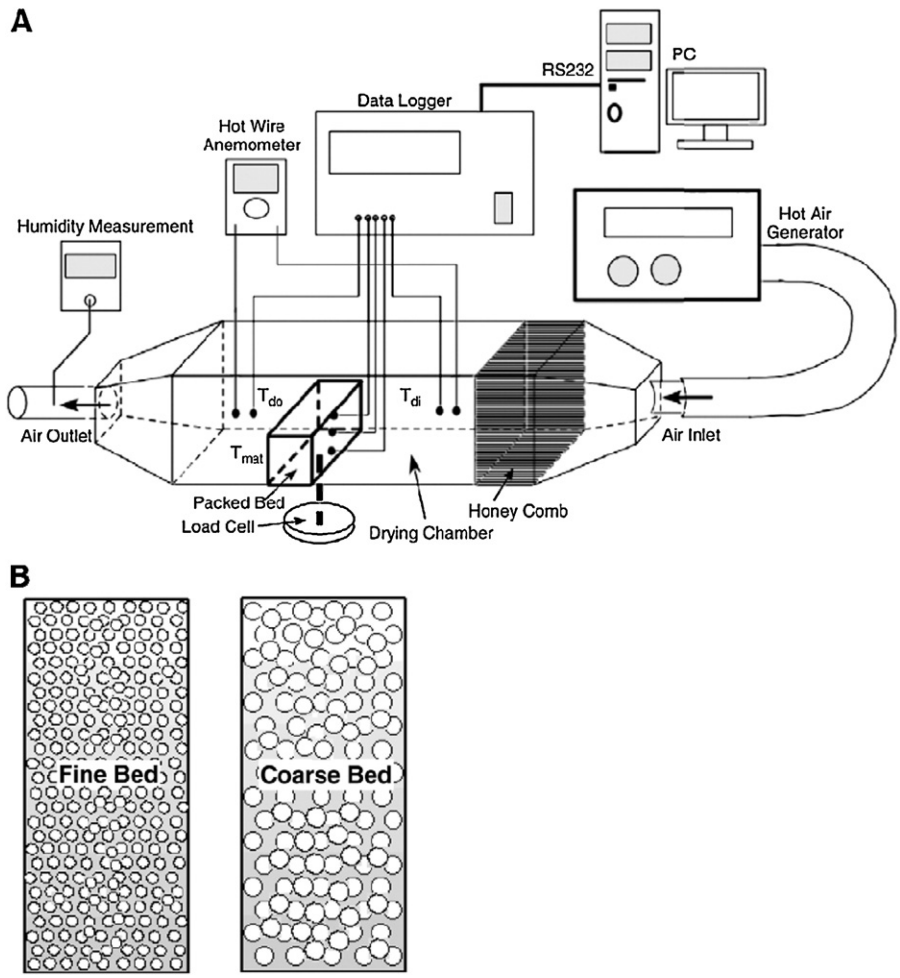

Fig. 9. (a) Equipment setup; (b) porous packed beds of different particle sizes.

of solar cell, tedlar back surface and greenhouse room air temperatures was approximately equivalent to the experimental values. The predicted and measured values of solar cell, tedlar back surface and greenhouse air temperatures was verified in terms of root mean square of percent deviation (7.05–17.58%) as well as correlation coefficient (0.95–0.97) and both exhibit fair agreement. Exergy analysis calculations of the PV/T integrated greenhouse system show an exergy efficiency level of approximately 4%.

Five different solar air heater was designed by the Kurtbas and Durmus [25] with the aim of effective way to save energy by increasing the efficiency in a solar collector by the heat transfer coefficient. It was concluded during the experiments that the efficiency of air collectors depends on surface geometry of the collectors and extension of the air flow line. The exergy loss of the system decreases depending on the increase of the collector efficiency. There is a reverse relationship between dimensionless exergy loss and the heat transfer, as well as pressure loss. The more important parameters in order to decrease the exergy loss are the collector efficiency, temperature difference of the air and pressure loss.

Jackfruit leather was dried from initial moisture content 76% (w.b) to 11.88% (w.b) in a solar tunnel dryer under Bangladesh climatic condition by Chowdhury et al. [26]. The energy and exergy for the same was also carried out by the authors. Their experimental results show that the energy efficiency of collector and dryer varied between 27.45 and 42.50% and between 32.34 and 65.30% respectively for the variation in solar radiation between 100 and 600 W m^{-2}. The overall energy efficiency of the solar dryer was 42.47%. The exergetic efficiency of collector and the mean value of the exergetic efficiency of dryer were 32.69% and 41.42% respectively. It was concluded that the exergy input and exergy loss for the dryer increased with increasing solar radiation.

An experiment on indirect type solar dryer as shown in Fig. 8 for drying mint under climatic conditions of Bouzareah on the heights of Algiers in the summer season was conducted by Boulemtafes-Boukadoum and Benzaoui [27]. They also discuss the exergy analysis to estimate the energy losses during the drying process.

Prommas et al. [15] investigated the energy and exergy analyses in drying process of porous media using hot air with the aim to evaluate (i) the exergy losses of two operations porous packed bed, (ii) the distributions of the exergy losses and exergy input of the different drying operations and (iii) the influences of operating parameters on exergy losses. The experimental setup of convective drying system and packed beds composed of glass beads, water and air is illustrated in Fig. 9. It was found that the exergetic efficiency of the drying chamber increased with the increase of drying time. This is because during the drying process the available energy in the drying chamber increases with drying time, since the amount of moisture decreases with time. Then, the effect of the other particle size on the drying time as well as the exergy efficiency of the drying system is presented. Furthermore, the exergy efficiencies of C-bed were observed to be higher than the F-bed about 10% after 60 min of drying time with parallel to the end of drying process.

3. Conclusion

In this review, energy and exergy analysis of different solar dryer were made and following conclusions can be drawn:

1. The exergy efficiency is actual efficiency of the process because of the irreversibility. It is found from case studies that, the total energy efficiency is high in spite of low total exergy efficiency.
2. The energy used in drying of agricultural and industrial produce is significant and, therefore, represents an often reducible element of process cost.

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